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Energy thresholds in the magnetic vortex core reversal

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Abstract. Owing to its small size and high stability, the core of magnetic vortices has been proposed as a possible candidate for binary data storage. We have investigated the energetic aspect of the vortex core reversal in ferromagnetic thin-film elements by means of fully three-dimensional finite-element micromagnetic simulations. The simulations show that the reversal occurs once a well-defined threshold in the exchange energy density is reached. We establish the energetic origin of the core reversal by demonstrating that this threshold corresponds to the energy necessary for the production of a vortex-antivortex pair. The effect of the discretization size on the computed exchange energy of a magnetic singularity is discussed. Such a singularity is required for the core reversal process to unfold.

1. Introduction

The vortex is a naturally forming structure, which closes the flux in ferromagnetic thin-film elements. It is characterized by an in-plane curling of the magnetization around a narrow core only a few tens of nanometers in diameter where the magnetization is perpendicular to the film plane [1]. Owing to the very high stability of the core, its reversal is one of the most dramatic transformations of a vortex. One method for reversing the core consists in applying a static field of the order of a few hundreds of mT in the direction opposite to the core orientation [2,3]. Another method, which requires considerably weaker fields, consists in dynamically switching the core by means of in-plane AC excitations [4] or single in-plane field pulses [5,6,7]. In the same manner, the core reversal can be triggered using in-plane alternating spin-polarized AC currents [8] or pulses [9,10]. In all these cases, the reversal of the core orientation is mediated by the same series of complex processes: first, a transient vortex-antivortex pair is produced, followed by the annihilation of the original vortex with the newly formed antivortex [4,5,6]. The reversal unfolds over only a few tens of picoseconds and represents the fastest magnetization switching process known in micromagnetic theory [6].

The above results show that there are two distinct routes allowing to dynamically trigger the vortex core reversal using in-plane fields or spin-polarized currents. In the first case, the gyrotropic mode of the vortex is excited by applying an in-plane sinusoidal excitation tuned at the vortex resonant frequency [4,8]. This frequency is typically below one GHz in mesoscopic thin film elements [11], such that the switching time is of the order of a few to tens of nanoseconds. In contrast to this *resonant* switching, a second route, which consists in triggering the core reversal using *non-resonant* pulses,

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allows to switch the core orientation within only a few hundreds of picoseconds. While the micromagnetic mechanism is identical in both cases, the switching times can therefore differ by up to an order of magnitude. To understand the origin of this difference, we searched for the fundamental physical parameter that triggers the core reversal. It has been suggested in Refs. [8,12] that the reversal is driven by a dynamic ‘gyrofield’ generated by the moving vortex. In this context, the core switch is predicted to occur for a critical velocity of the driven vortex [8,13] in analogy to the Walker breakdown of domain walls [14]. While this interpretation allows associating a measurable parameter to the core reversal, it does not explain the creation of a new vortex-antivortex pair, *i.e.* the micromagnetic mechanism of the reversal. In addition, at the critical velocity, the gyrofield was found to diverge [12]. We therefore adopted a different approach and studied the evolution of the vortex energy.

Considering the case of the current-driven core reversal, we found that the core orientation reverses once a well-defined critical value of the exchange energy is reached. Our simulations further show that under the influence of an in-plane spin-polarized current, the increase in exchange energy of the moving vortex is due to: 1) the distortion of the vortex in-plane structure, 2) the contraction of the moving core radius and 3) the formation of a new vortex-antivortex pair in the sample. The first two effects only account for less than 1% of the exchange energy increase at the moment of the core switch. The observed energy threshold is therefore due to the formation of a new pair, evidencing the energetic origin of the vortex core reversal.

2. Micromagnetic simulations

The results were obtained using our micromagnetic finite-element code [9] based on the Gilbert equation, including the adiabatic and non-adiabatic spin torque terms [15,16]:

$$\frac{d\mathbf{m}}{dt} = -\gamma(\mathbf{m} \times \mathbf{H}_{\text{eff}}) + \alpha \left(\mathbf{m} \times \frac{d\mathbf{m}}{dt} \right) - (\mathbf{u} \cdot \nabla) \mathbf{m} + \beta \mathbf{m} \times [(\mathbf{u} \cdot \nabla) \mathbf{m}]$$

where $\mathbf{m} = \mathbf{M}/M_s$ is the local reduced magnetization, M_s the saturation magnetization, α the Gilbert damping constant, β the strength of the nonadiabatic torque term, and γ the gyromagnetic ratio. The vector \mathbf{u} is in the direction of the electron flow and has an amplitude of $u = jPg\mu_B/(2eM_s)$, where j is the current density, P the degree of polarization, g the Landé factor, μ_B the Bohr magneton and e the electron charge. The effective field \mathbf{H}_{eff} is the negative variational derivative of the local energy density e with respect to the magnetization: $\mu_0 \mathbf{H}_{\text{eff}} = -\delta e / \delta \mathbf{M}$. The energy density takes into account contributions from the magnetostatic, exchange and anisotropy terms.

We performed simulations for a Permalloy (Py) disk of radius 100 nm and thickness 20 nm using the following parameters: $A=13$ pJ/m (exchange constant), $\mu_0 M_s=1.0$ T, $\alpha=0.01$, $K_s=0.10$ mJ/m² [17] (surface anisotropy), $\beta=0.02$ [16] and $P=0.7$ [18]. The sample was discretized into 150,780 irregular tetrahedral elements, corresponding to an average cell size of (1.6 nm)³. The magnetization is computed at the apexes of the elements and the vector field is linearly interpolated within the elements. The demagnetizing field is computed using a combined finite element-boundary element method [19]. The surface anisotropy energy is calculated by integrating over the triangular boundary elements with the same value of K_s assumed at the top and bottom surfaces. Time integration is performed using the Adams method with adaptive time intervals in the sub-picosecond range. A homogeneous current density distribution was assumed.

3. Energy thresholds for resonant and non-resonant switching

We investigated the time evolution of the vortex energy during the core switch for the resonant and non-resonant switching pathways. Our analysis shows that the core reversal is connected to a well-defined critical threshold value of exchange energy in both cases.

3.1. Resonant switching

We first consider the case when the vortex is driven by a resonant current $j(t) = J \sin(\omega t)$, where J is

the current amplitude and ω_0 the vortex resonant frequency, which is a function of the sample aspect ratio. For our sample, we determined numerically $\omega_0 = 776$ MHz, in very good agreement with the analytical model in Ref. [11]. In this case, the minimum current density required to trigger the vortex core reversal is of $J = 4 \times 10^{11}$ A/m². The reversal occurs after approximately 14 ns. Increasing J leads to faster switching, of the order of a few nanoseconds as shown in figure 1.

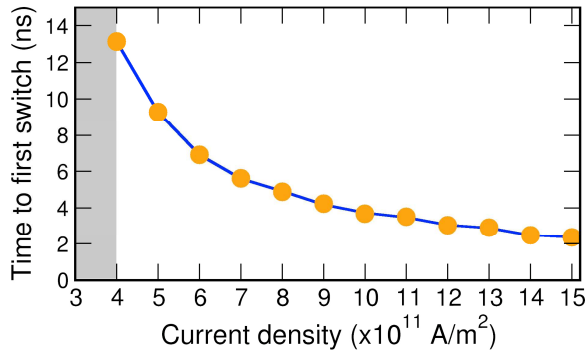


Figure 1. Vortex core switching time as a function of the resonant current amplitude. The switching time is defined from the moment an electric current is applied. No reversal occurs in the grey shaded region.

The time evolution of the average energy densities in the sample is shown in figure 2 for a current amplitude of $J = 1.2 \times 10^{12}$ A/m². As long as the current is applied, the core periodically reverses its polarization. Each switching event is clearly distinguishable by an increase in the total energy, followed by a sudden drop connected to the vortex-antivortex annihilation [20]. We found that the reversal is characterized by sharp peaks in the exchange energy. Considering in parallel the evolution of the magnetization, we have determined that these peaks correspond to the production of a new vortex-antivortex pair prior to each switching event. In contrast, the observed peaks in the magnetostatic energy density result from finite-size effects, *e.g.* the proximity of the excited vortex to the sample edge.

Following the reversal, the resulting spin waves [20,21] lead to magnetic ringing. Clearly, the switching events occur once specific total and exchange energy densities are reached, demonstrating the existence of well-defined switching thresholds. We also note that the surface anisotropy energy does not show important variations (maximum 2%) during the reversal process.

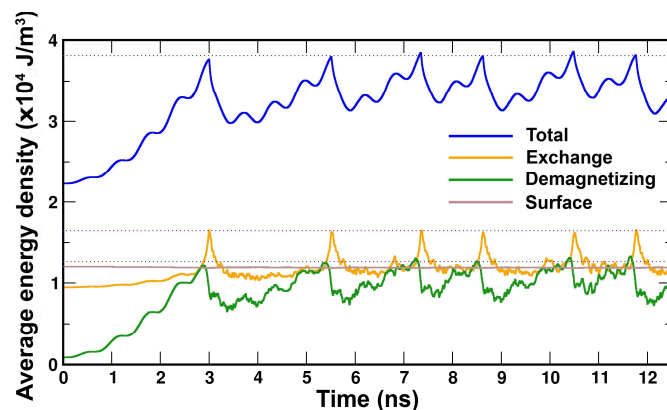


Figure 2. Evolution of the total and partial energy densities during the core reversal under the influence of an alternating current of maximal amplitude $J = 1.2 \times 10^{12}$ A/m². The dotted lines indicate the energy density thresholds (peak averages). The total energy is the sum of the exchange, demagnetizing and surface terms.

3.2. Non-resonant switching

The time evolution of the internal energy when the core switch is triggered by a non-resonant Gaussian pulse is shown in figure 3. Peaks in the exchange and total energy densities, followed by a sharp drop, equally accompany the reversal process. For the studied sample geometry, a minimum current of $J = 7.3 \times 10^{11}$ A/m² is required for the switch to occur.

Remarkably, we find that the exchange energy density threshold is the same within 2% for both the

resonant and non-resonant reversal routes. We moreover found that it is independent of the applied current amplitude. From the data in sections 3.1 and 3.2, the average increase in exchange energy density at the moment of the reversal is $\Delta e_{\text{thresh}} = (0.59 \pm 0.01) \times 10^4 \text{ J/m}^3$, where Δe_{thresh} is the difference between the static energy of the vortex and the energy at the moment of the switch.

Moreover, we find that the radius at which the core reversal occurs is the same for both the resonant and non-resonant pathways and is equally independent of the current strength. The threshold in magnetostatic energy density is also within 2% for both reversal pathways.

If energy is indeed the fundamental parameter determining the core reversal, the above threshold should not be affected by variations in the driving current parameters or in intrinsic properties of the sample, such as the damping constant. In the following, we study the influence of the current polarization and the damping constant α on the switching threshold.

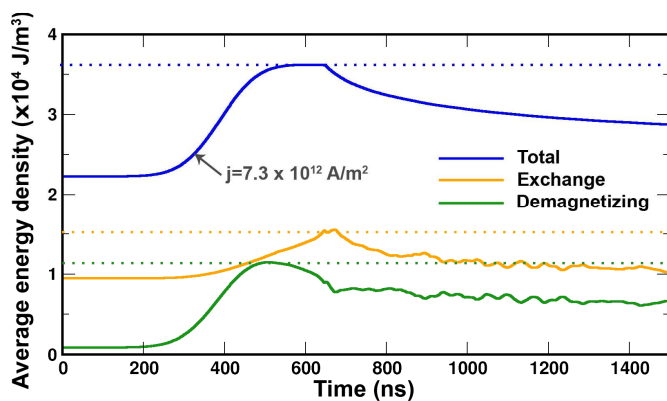


Figure 3. Evolution of the partial and total energy densities for the core switch triggered by a Gaussian current pulse of strength $J = 7.3 \times 10^{11} \text{ A/m}^2$ and width $\sigma = 100 \text{ ps}$ [9]. The dashed lines indicate the threshold energy densities.

4. Threshold invariance

4.1. Under variation of the current polarization

To verify the influence of the current polarization on the switching thresholds, the core was reversed by means of single in-plane field pulses as described in section 3.2. The width of the Gaussian pulses was kept at 100 ps and their strength varied for different values of the polarization P . Figure 4 shows that the value of the partial energy densities at the moment of the reversal are independent of the current polarization. Clearly, for the reversal to occur, the exchange energy in the sample must increase by Δe_{thresh} as found in section 3.2. In contrast, the inset of figure 4 shows the minimum switching current as a function of its polarization.

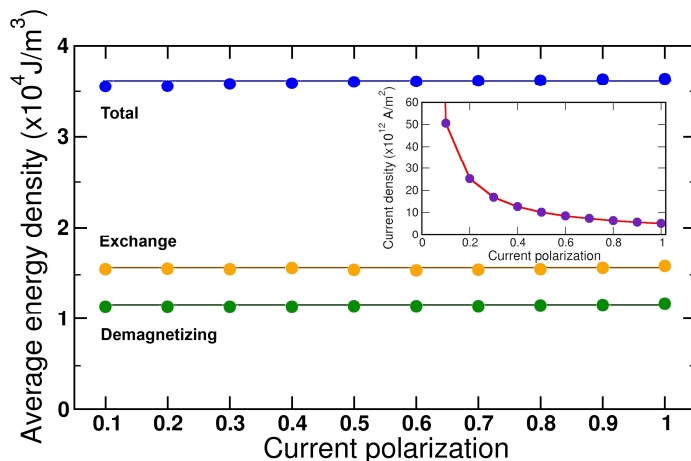


Figure 4. Average energy densities at the moment of the core switch as a function of the driving current polarization. The switch is triggered by non-resonant pulses as in Figure 3. The full lines indicate the average threshold value for each energy contribution. Inset: Current densities required to trigger the vortex core reversal as a function of the current polarization.

4.2. Under variation of the damping constant

The inset in figure 5 shows the behavior of the minimum current density required to reverse the core as a function of the damping coefficient α using a resonant excitation.

We show in Figure 5 that the switching energies are again invariant, with an average value within about 2% of the values found in figure 4. We note that following section 3, the threshold energies are independent of the excitation type, such that the results obtained for the energies in 4.1 and 4.2 hold for both resonant and non-resonant excitations.

A further analysis of the influence of other parameters such as the sample radius and thickness will be presented elsewhere.

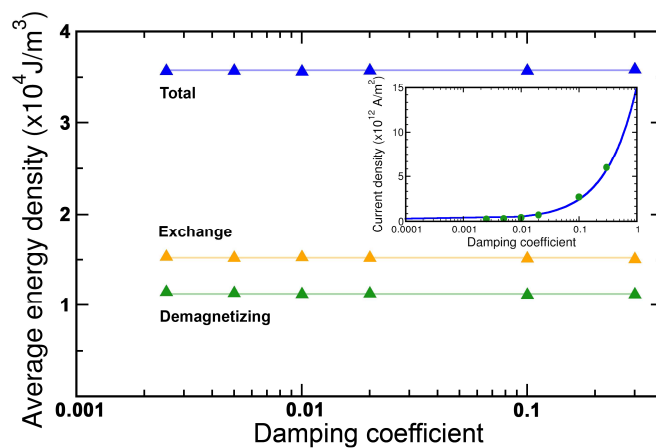


Figure 5. Average energy densities at the moment of the core switch as a function of the damping coefficient α . The switch is triggered by resonant excitations as in Figure 2. Inset: Evolution of the resonant current amplitude required to trigger the core reversal as a function of the damping coefficient α . The data (solid green circles) is fitted to a power function (blue line).

5. Vortex-antivortex pair energy

So far, we established the invariance of the switching energy thresholds with respect to extrinsic as well as intrinsic parameters of the vortex. In addition, we found that the exchange energy density Δe_{thresh} required for the core reversal to occur is connected the formation of a vortex-antivortex pair.

According to Refs. [22,23], the exchange energy of a pair is $E_{\text{pair}} = 8\pi Ah$, with A the exchange constant and h the sample thickness. In our sample, an increase in exchange energy by E_{pair} would correspond to an average exchange energy density increase of $\Delta e_{\text{pair}} = 1.04 \times 10^4 \text{ J/m}^3$. In comparison, the threshold value Δe_{thresh} obtained in 3.2 from the simulations only represents about 60% of the energy of a vortex-antivortex pair in Py. As a further example, we have also investigated the energy evolution during the core switch in Iron (Fe: $A = 21 \text{ pJ/m}$, $\mu_0 M_s = 2.15 \text{ T}$). In this case, our simulations show that the switching threshold energy is of the order of only 40% of that required for pair production. We attribute these material-dependent discrepancies to the presence of a Bloch point in the sample. Indeed, the core reversal is mediated by the formation and propagation of a singularity [6,20]. In this case, the computed exchange energy is strongly dependent on the discretization cell size [3].

In order to determine the accurate value of the exchange energy density at the moment of the core reversal, we varied the distance between discretization nodes in our simulations and extrapolated the switching energy at zero cell size. The results are shown for both Py and Fe in figure 6 where the value of Δe_{thresh} is expressed in units of $8\pi Ah$. Fits to the data show an exponential behaviour of the switching energy as a function of the distance Δx between discretization nodes. At zero cell size we find that Δe_{thresh} indeed converges to $8\pi Ah$ for both materials.

6. Conclusions

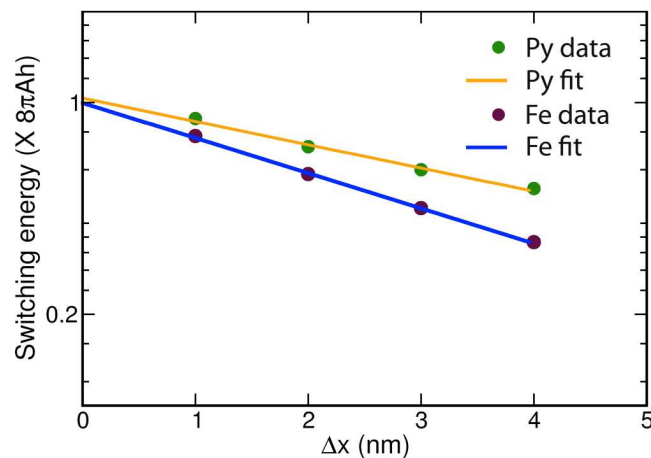


Figure 6. Evolution of the exchange energy threshold in Py and Fe as a function of the average distance Δx between neighboring discretization points. The best fit to the data is given by an exponential function. A distance of one nm between nodes approximately corresponds to an equivalent cubic cell of $(0.5 \text{ nm})^3$.

We investigated the time evolution of the magnetic energy during the vortex core reversal for the resonant and non-resonant switching pathways. The simulations demonstrate that in both cases a well-defined exchange energy barrier has to be overcome in order to trigger the vortex core reversal. This switching threshold does not depend on the type of excitation and is equally independent of the amplitude and polarization of the applied spin-polarized current as well as of the value of the damping constant.

Because the reversal process involves a magnetic singularity, in order to accurately determine the exchange energy at the moment of the reversal, we have extrapolated this energy for a vanishing distance between discretization nodes. We found that the value of the exchange threshold corresponds to the analytically predicted energy required for the formation of a new vortex-antivortex pair. This provides evidence for the energetic origin of the micromagnetic mechanism driving the core reversal. A link between the critical velocities found in Refs. [10,12,13] and the threshold energy remains to be established.

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